RF SYSTEMS (WBS 1.7)

i. General Considerations

The rf system must be capable of capturing, accelerating and storing for many hours up to 60 bunches of particles corresponding to an average electric current of 70 mA. Particle species vary from protons to fully stripped gold ions. Each function places certain requirements on the overall system design. In fact operation of RHIC will require three individual rf systems, each of which can function independently of the other two.

- The acceleration system performs the capture of the injected bunches, acceleration through transition, and bunch shortening at top energy. This system operates at the harmonic number $h = 360$ of the particle rotation frequency $f = 78.196$ kHz, i.e., at 28.15 MHz.
- The storage system accepts the shortened bunches at top energy and provides sufficient longitudinal focussing to keep these bunches short during the 10-hour storage time (i.e., in the colliding mode). The storage system operates at harmonic number $h = 7 \times 360 = 2520$, corresponding to an rf frequency of 197.05 MHz. The storage system should work at an integer multiple of the acceleration system to preserve the possibility of increasing the number of circulating bunches from 60 to 72, 90 or 120.
- The wideband system damps longitudinal injection errors of a single bunch or groups of bunches and provides control of coupled-bunch instabilities. It consists of a separate, low-voltage, wide-bandwidth cavity for each ring, operating at harmonic numbers 360±60 in the frequency range 23 to 33 MHz.

A more detailed description of these systems and their functions at crucial points of the machine cycle will be given in the following paragraphs. A survey of hardware implementations is presented at the end of the section.

The Acceleration rf System

The choice of $h = 360$ or $f_{rf} \approx 28.15$ MHz for acceleration has been made to provide the maximum flexibility in bunch filling patterns for experiments. It provides buckets of ample phase width to accept the proton and heavy ion bunches from the AGS without introducing excessive nonlinearity for bunches that arrive off-center due to injection errors. A gold bunch of 0.5 eV·s/u area in the AGS at V_{rf} = 320 kV (f_{rf} = 2.97 MHz) has a length of 21 nsec or 213^{o} in a 28.15 MHz RHIC bucket while proton bunches of the same area will be even shorter (170^{o}), and direct transfer of bunches is thus possible. The voltage required to produce a bucket to match these bunches is 150 kV for Au, but only 14 kV for protons since their injection energy is much closer to, albeit above, the transition energy. In the case of gold, the resulting bucket area is marginal and, in the case of protons, beam loading at this low voltage is expected to be strong. In order to avoid complications a higher voltage, about 300 kV, is needed in RHIC, and a reversible bunch rotation (reversible to allow single bunch transfer) in the AGS is required

The acceleration rate is determined by the ramp rate of the magnetic field $\dot{B}$ which for RHIC is 0.042 T/s. This results in a 75 sec acceleration period and requires that V sinö$_s$ = 47.4 kV/turn for all species. Taking V = 300 kV then we find that ö$_s$ = 9^{o} and in the case of Au this results in the initial bucket area of (0.72 × 1.1) = 0.79 eV·s/u. In fact since the bucket area grows with energy at fixed voltage and ö$_s$ until the transition energy is reached, the voltage could be reduced as a function of time while still maintaining ample room for the bunches. For protons and lighter ions the initial acceleration voltage can be lower.

Table 7-1 gives beam acceleration and rf bucket parameters for Gold ions. The local convention assumes bunches with bi-Gaussian density distribution, and quotes dimensions holding ~95% of all particles. For an rms energy spread ó$_E$ and rms bunch length ó$_\ell$, the bunch area thus defined is S = 6ð ó$_E$ ó$_\ell$/c, the total (double-sided) energy spread $2\sqrt{6}$ ó$_E$, and the total bunch length $2\sqrt{6}$ ó$_\ell$ (or alternatively 2.081 × full width at half height).

Transition Crossing

With the exception of protons, all ions are injected below the transition energy (ã$_T$ = 22.89) and, consequently, have to be accelerated through transition to reach the top energy for storage. In order to successfully transfer the ion beams from the acceleration rf system (28.15 MHz) to the storage rf system (~197 MHz) without particle loss, it is of primary importance to restrain the bunch area growth during the transition crossing to less than 0.7 eV·s/u. A bunch area at injection in the range from 0.3 to 0.5 eV·s/u is thus acceptable.

Problems related to transition crossing can be divided into two categories: single- and multi-particle. The former category mainly includes the effect of chromatic non-linearities, while the latter includes bunch-shape mismatch and microwave instability induced by low- and high-frequency

Table 7-1. Beam Acceleration and rf Bucket Parameters (Au)

	AGS	RHIC Injection	RHIC Transition†	RHIC Top	Units
ã	12.6	12.6	24.7	108.4	
Q	77^+	79^+	79^+	79^+	
Bÿ	0	0	500	0	G/sec
V_{rf}	320	300	300	300	kV
S	0.5	0.5	0.5	0.7	eV·s/u
Ä*E/E*	±1.1	±1.5	±5.6	±0.15	$\times 10^{-3}$
ó$_{\ell}$	1.4	1.1	0.18	0.19	m
A_{bucket}	53.3	1.1		5.8	eV·s/u

†Without ã$_T$-jump.

self fields, respectively. In addition, the remnant voltage of the 197 MHz rf cavities induced by the circulating beam causes further complication and must be limited.

It has been shown that, in the absence of a ã$_T$-jump, the chromatic non-linear effect, which is enhanced by the space-charge mismatch, causes severe beam loss during the transition crossing. Besides, the beam is near the microwave-instability threshold.

An effective way to cure the undesired effects is to increase the transition-crossing rate of the beam. This can practically be accomplished either by temporarily adjusting the lattice to achieve a ã$_T$-jump, or by manipulating the synchronous phase to achieve a larger acceleration rate. Computer simulation indicates that the method of ã$_T$-jump provides a large crossing-rate enhancement without causing severe mismatch at transition.

Both analytical and numerical studies have been performed to investigate the various problems. It has been shown that the transition crossing can be achieved with no particle loss and the bunch-area growth limited to 0.7 eV·s/u, when a ã$_T$-jump of 0.8 unit is employed in a time period of 60 ms. The maximum tolerance on the remnant voltage of the 197 MHz rf system is 10 kV. The peak voltage is kept at 300 kV during the entire process.

During the period of acceleration, measures are taken to minimize the voltage of the storage rf system. The effect of the remnant voltage becomes significant only during the time of transition crossing when the particle motion is non-adiabatic. With the ã$_T$-jump, a maximum tolerable voltage of 10 kV has been obtained to avoid bunch-area growth.

Shortening of the Bunches for Transfer to the Storage rf

The bunch length has to be reduced by manipulations in the accelerating system before the transfer to the storage system can be performed, where the 197.1 MHz bucket is only 1.52 m or 5.1 nsec long.

Adiabatic bunch compression has been considered to achieve this goal. However, for a compressed bunch length ô at the end of the process, an rf voltage proportional to ô$^{-4}$ is necessary. This exponent of four leads to excessively high rf voltages, as the case of gold ions at the top energy of 100 GeV/u exemplifies: a voltage of 700 kV would just permit to compress the bunches into the length of the receiving bucket, but 2.2 MV would be required for a safe length of 1.14 m corresponding to a 270^o width.

The alternative method of bunch rotation will therefore be applied to shorten the bunches. Here the required voltage is proportional to ô$^{-2}$ and, hence, considerably lower; only 293 kV are required to produce a bunch 270^o wide under the same conditions as above. The procedure is started with a slow, adiabatic reduction of the rf voltage down to V_1, close to the minimum value that allows safe holding of the beam. This leads to a bunch of low energy spread and wide width ô$_1$, i.e. to an extremely oblong contour. The subsequent bunch rotation process proper depends on voltage changes that are non-adiabatic, i.e. fast in comparison to the phase oscillation period ô$_0$, to essentially preserve that oblong contour as illustrated in Fig. 7-1. The voltage is rapidly increased from V_1 to the maximum available voltage V_2 to start rotation of the bunch in phase space with near uniform angular velocity. After a quarter turn, the voltage is rapidly reduced to nominally zero and the bunches, now in position of smallest projection to the time axis, are taken over by the storage system.

Disadvantages of this method include possible distortion (filamentation) of the bunch shape due to bucket non-linearities, and hardware complications due to the fast amplitude changes. Simulation studies have shown that transfer with very little particle loss can be achieved for a voltage raised from 20 kV to 350 kV in 100 µsec. This requires additional power capabilities from the rf amplifiers, since the cavities have to be forced to respond in approximately half of their natural time constant.

The accelerating system will be designed for a nominal voltage of ≥600 kV to provide some flexibility in operating conditions, and for a frequency swing of 1% to permit acceleration as well as deceleration of the heavier ions.

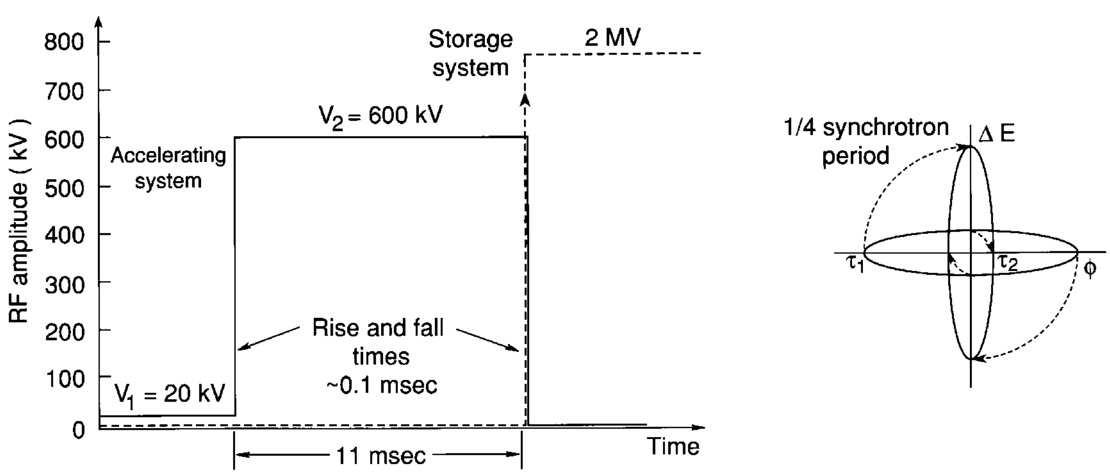

Fig. 7-1. Bunch rotation and subsequent beam transfer.
(a) timing (b) bunch rotation in phase space

The Storage rf System

The storage mode system has to take over the bunches after the acceleration process and hold them during the 10-hour storage time. The choice of the frequency is a compromise between competing factors. Intrabeam scattering leads to considerable longitudinal blow-up during the storage period, and strong rf focussing is therefore necessary to keep the bunch length sufficiently short, which can best be achieved by high frequencies. On the other hand, the growing energy spread requires a considerable bucket height, which favors the use of low frequencies.

Closer analysis based on beam tracking simulation has shown that frequencies between 150 MHz and 200 MHz are usable. Higher frequencies in this band allow shorter bunch length but complicate the beam transfer, require higher rf voltages and increase cost. The end storage system should work at an integer multiple of 28.15 MHz to insure the maximum flexibility in bunch filling patterns.

Due to hardware availability considerations, a frequency of 197.05 MHz has been chosen, which corresponds to a harmonic number $h = 360 \times 7 = 2520$.

Voltage Requirement of Storage rf

The initial voltage requirement of the storage rf system is determined by the bucket half height $Ä_B$,

$$V = \frac{ð}{2} \, \frac{h|ç|ãE_0}{â^2 e} \, \frac{A}{Q} \, Ä_B^2$$

with $ç = ã_{tr}^2 - ã^2$ and A the atomic mass unit and Q the charge state. In the case of Au bunches with an area of 0.3 eV·sec/u at top energy, the energy spread is $Ä_E = ÄE/E = 54.1 \times 10^{-3}$ immediately after transfer into 270º of the 197.05 MHz system. The required bucket height is $Ä_B = 1.08\, Ä_E$ and the corresponding matched voltage is ~575 kV.

The final voltage required after a 10-hour storage period depends on the growth of the bunch due to intrabeam scattering, which in turn depends on the initial transverse emittance and on the details of the rf voltage program. Figure 7-2 shows the necessary final voltage for the "tight bucket" scenario. Here the rf voltage is programmed to start low and to grow together with the beam, always providing a bucket that is about twice as high as the rms energy spread of the bunch. The final rf voltage required for gold beams at 100 GeV/u with an initial normalized emittance of 10ð mm mrad is nominally ~16 MV in the tight bucket scenario.

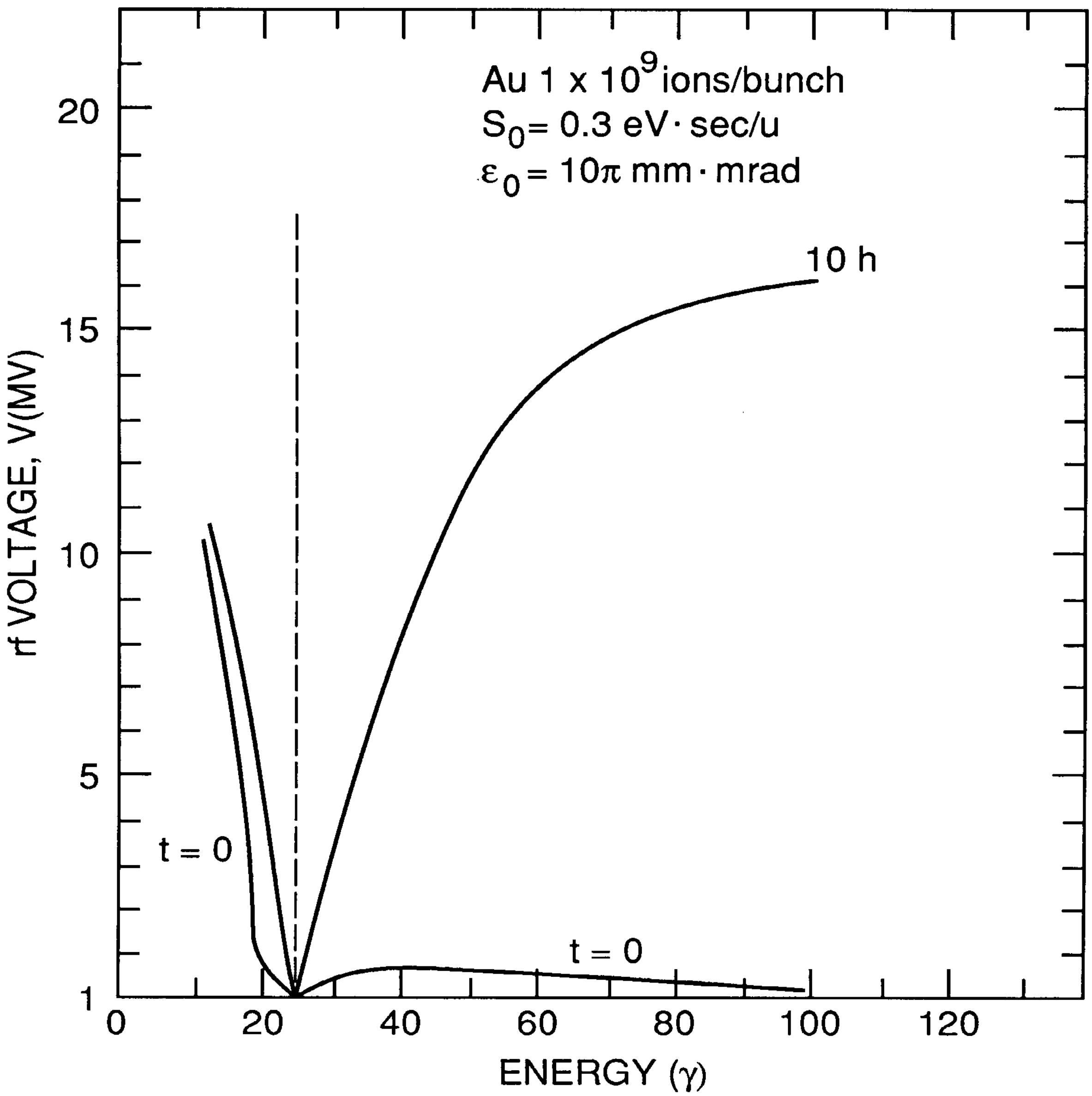

Fig. 7-2. Dependence of storage rf voltage requirement on energy ("tight bucket" scenario).

Later studies have shown that the reduced bucket dimensions lead to considerable beam loss during the storage period. This beam loss can be reduced by the "constant voltage" scenario; here the rf voltage is matched to the bunch dimension only at beam transfer, then adiabatically raised and held at the full available amplitude from the very beginning of the storage period. Results of simulation studies are given in Fig. 7-3.

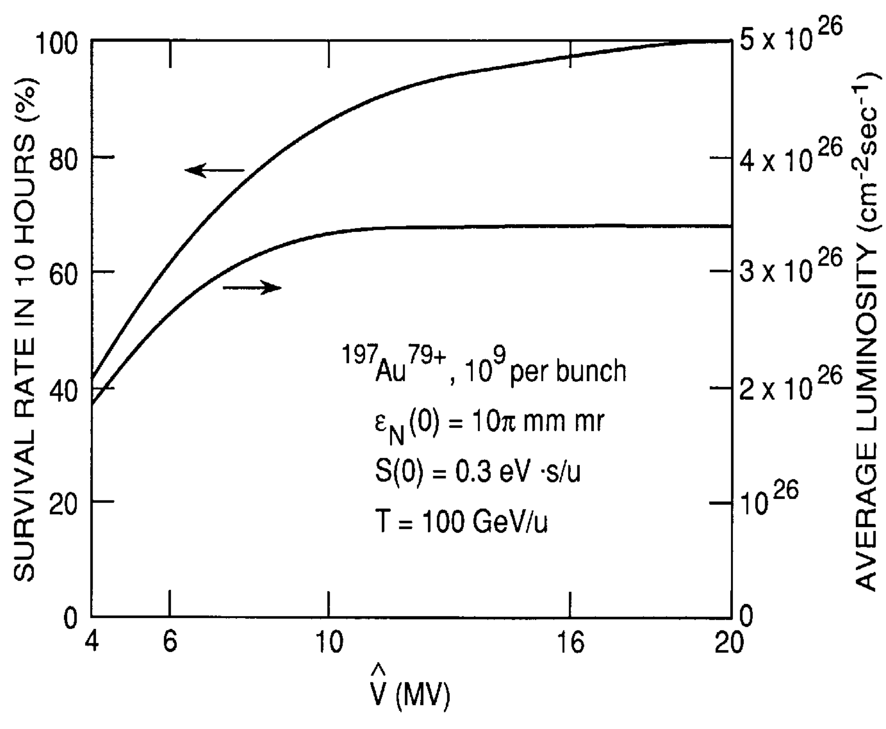

Fig. 7-3. Dependence of final beam survival rate and average luminosity on storage rf voltage after 10-hour operation, "constant voltage" scenario (courtesy J. Wei).

It can be seen that voltages in excess of 10 MV, while increasing the beam survival rate, have very little effect on the average luminosity. On the other hand, a relatively modest rf voltage of 6 MV can provide ~78% of the maximum attainable average luminosity, even if the beam survival rate after 10 hours is only about 62%.

Very similar results are obtainable if the rf storage voltage is applied in full immediately after beam transfer, rather than adiabatically raised from matched conditions. The design goal for the slow rate of the storage cavities aims therefore at a voltage somewhat higher than the matched value (namely, 770 kV), in order to have room for optimization under actual operating conditions.

The differential equations governing intrabeam scattering are believed to be well-understood and reliable. There are, however, uncertainties resulting from the lack of knowledge as to the beam parameters in RHIC after injection and acceleration through transition. In view of these uncertainties which mostly impact the rf voltage requirements and the substantial cost attached to the high-frequency rf system, installation of a lower voltage rf system on day-one would seem advisable.

It was decided to provide a storage system initially capable of 6 MV/ring. The resulting average luminosity is satisfactory, the beam losses, although on the high side, are believed to be tolerable since distributed over the storage cycle and concentrated around the collimators. The space in the ring allows the addition of cavities at a later date to increase the rf voltage if necessary. Alternatively, the possibility of adding longitudinal stochastic cooling is being seriously considered. Damping rates of ~0.1/hour would allow long-term storage of beams with the small emittances expected from the injector. However, transverse cooling is required to avoid any loss in luminosity.

The Wide Band System

The chief purpose of this system is to damp longitudinal injection errors before the resulting coherent synchrotron oscillations can cause significant bunch area dilution due to the nonlinearity of the rf focusing force. This is necessary since the bunches must eventually be compressed into 197.05 MHz buckets with some safety margin. One can write

$$\frac{\text{Ä}A}{A} = \frac{2\text{ä}\varphi}{\hat{\varphi}} = \frac{2\text{ä}p}{\text{Ä}p}$$

where A is the bunch area, ΔA is the dilution due to a phase error $\delta\varphi$ or a momentum error $\delta p/p$ for a bunch whose half length is $\hat{\varphi}$ or half height is $\Delta p/p$. Considering the case of 0.3 eV sec/u at injection, where $\hat{\varphi} = 74^o$ at 28.15 MHz and $\Delta p/p = 1\times10^{-3}$ for Au-bunches with V_{342} = 215 kV, and assuming $\delta p/p \approx 10^{-4}$ one finds $\Delta A/A \approx 0.2$ if uncorrected. The corresponding phase error of the center of that bunch is $\delta\varphi \approx 8.2^o$ and the position error at X_p = 1.5 m would be 0.16 mm. The decoherence time i.e. the time required for particles on opposite sides (momentum error) or ends (phase error) of the bunch to overlap in phase space is $\Delta\tau = 2\pi/2\Delta\omega_s$ where $\Delta\omega_s \approx (\omega_{so}/4)\ \hat{\varphi}\ \delta\varphi$ is the difference in synchrotron frequency of these particles and ω_{so} is the small-amplitude synchrotron frequency ($\hat{\varphi} \approx 0$). The decoherence time is 0.1 sec for these conditions.

Damping of these oscillations could be accomplished by phase modulation of the rf voltage seen by each bunch individually, with a signal proportional to the momentum (or position) error of the bunch relative to the center of the bucket defined by the h = 360 rf system. Alternately, the correction signal could be derived from the phase error between the bunch center and the rf voltage (a delay of $\tau_\phi/4$ or 90^o , at ω_ϕ would be required to produce damping). Since the bandwidth of the h = 360 rf system will not permit this, effective phase modulation is obtained by exciting the wideband cavity with gated bursts of rf signal at 28.15 MHz that is shifted 90^o in phase with respect to the main rf voltage (e.g. 215 kV for Au at injection). For linear feedback the error will decay like $\Delta p_e = \delta p \exp(-t/T)$ and similarly for a phase error $\delta\varphi$. Thus at $t = 0$, $\Delta\dot{p}_e = -\delta p/T$ from which follows the maximum voltage V_e required to provide a given (1/e) damping time T. One can write

$$V_e = \frac{1}{T\,f_o}\ \frac{\beta\ pc}{e}\ \frac{A}{Q}\ \frac{\delta p}{p}$$

with f_o the revolution frequency and Q the ion charge state. A damping time of T = 0.1 sec which is equal to the decoherence time is obtained with V_e = 327 V. However this must be multiplied by 2 since the effective damping averaged over a synchrotron period is reduced by 1/2 (assuming that $T \gg \tau_{so}$).

The damping rate can be increased by programming the feedback loop to apply the same correction voltage as long as the error remains above some minimum value. Thus a choice of nonlinear feedback and a maximum correction signal of ~700 V would reduce a 10^{-4} error to 10^{-5} in 77 msec. Longitudinal tracking analysis has indicated that a 1000 V damper will limit emittance growth due to injection errors to less than 10%. This will be the design goal for the wideband rf system. It should be noted that the bandwidth of this system will also allow it to control any coupled-bunch dipole instabilities that arise from incompletely damped parasitic resonances in the other two rf systems.